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COMMISSIONING

(PHASES 4, 4A, 4B)

FINAL TECHNICAL REPORT

by

A N Schofield and R S Steedman

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ANDREW N SCHOFIELD & ASSOCIATES LTD
9 LITTLE ST MARYS LANE,
CAMBRIDGE CB2 1RR, U.K.

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Name of Institution:	Andrew N Schofield & Associates Ltd., 9 Little St Marys Lane, Cambridge CB2 1RR, U.K.
Principal Investigator:	Dr Andrew N Schofield

A N Schofield R S Steedman 1 September 1997

SUMMARY

Phase 4 marked the completion of ANS&A's commitments under the BAA, as the new large centrifuge at the Waterways Experiment Station was commissioned and a series of research experiments were undertaken to demonstrate the breadth of new capabilities which have now been achieved in physical modeling through this research effort. Extensive work was undertaken in collaborating with potential users of the centrifuge, developing and refining their experiments, and in assembling and commissioning the equipment and appurtenances which had been designed in Cambridge to meet the perceived research needs. ANS&A research engineers were resident in Vicksburg for many months, providing support to WES staff in the commissioning of the centrifuge itself and in the completion of these early research experiments. Studies were accomplished in fields ranging from precision scale blast models of cratering to the formation of ice sheets under high gravity to the generation of strong earthquake-like shaking in a deep saturated soil specimen. The mechanical commissioning of the centrifuge was interrupted in January 1996 as a number of components were found to require replacement, and this was completed in August 1997. However, this delay in commissioning did not significantly affect the research programme planned for the facility as operations continued within a reduced operating enevelope. During this period ANS&A provided advice on operating procedures and completed planned research experiments, covering a wide range of required capabilities. The achievement of the full operating envelope of the centrifuge in September 1997 and the subsequent Inauguration on 20 November 1997 marked the formal opening of the Center.

LIST OF KEYWORDS

centrifuge
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model
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1.0 COMMISSIONING OF THE WES CENTRIFUGE CENTER

1.1 RESEARCH BACKGROUND

This report is one of a series of reports prepared by Andrew N Schofield & Associates Ltd (ANS&A) addressing the development and commissioning of new capabilities for physical modeling research at the Waterways Experiment Station (WES), through the acquisition of a powerful centrifuge facility. The research described herein forms Phase 4, 4A and 4B of the programme of work first proposed under ANS&A's response (of 17 April 1989) to the WES Broad Agency Announcement (BAA) of December 1988.

Phase 1 of this project, entitled "Safety Factor Analysis for Centrifuge Systems", addressed the specification, Quality Assurance (QA) procedures and safety of operations that would be required to successfully commission a new centrifuge center at WES. In the Final Technical Report under Phase 1 (Contract Number DAJA45-90-C-018), ANS&A (1992), it was recommended that WES should buy the Acutronic 684-1 centrifuge subject to the implementation of QA procedures designed to ensure the swift integration of the new facility into the research activities of WES, Schofield and Steedman (1991).

Phase 2 of this project (Contract number DAJA45-91-C-0012) entitled "Development of a WES Centrifuge" initiated the Quality Assurance process under which ANS&A worked with the Laboratories of the US Army Corps of Engineers through the Centrifuge Coordinating Committee to prepare specifications for appurtenances and data aquisition equipment that would be needed during the commissioning of capabilities. ANS&A's Phase 2 Final Technical Report made specific recommendations concerning the development of appurtenances for initial experiments which would be compatible with the design of the Acutronic 684-1 centrifuge, Schofield and Steedman (1992).

Phase 3A entitled "Centrifuge facility design and development of capabilities" (Contract number DAJA45-91-C-0025) and 3B "Report on Quality Assurance for the WES Centrifuge" (Contract number DAJA45-92-C-0021) addressed the continuing role of ANS&A in providing advice and guidance during the design phase of the WES Centrifuge by Acutronic France SA. ANS&A's Final Technical Report covering Phases 3A and 3B recommended acceptance of the detailed design of the Acutronic 684-1 centrifuge and that the operating envelope of the centrifuge be revised to maximise the potential capability of the facility in the mid-range of operating levels (150-350g), Schofield and Steedman (1993).

Phase 3C, entitled "Coordination of operations for centrifuge quality control" (Contract number DAJA45-93-C-0021), presented recommendations concerning the initial research experimentation on the WES centrifuge and addressed in detail the mechanical commissioning of the centrifuge following its arrival in Vicksburg. A key recommendation arising from Phase 3C was the separation of the initial mechanical commissioning (upto a level of around 250 gravities) from the final commissioning (to full capability) and the necessity for careful and close control of the commissioning operations, Schofield and Steedman (1995). This approach was considered essential because of the unique nature of the centrifuge and the uncertainty over the available Manufacturer's documentation concerning Quality Control.

Phase 3D, entitled "Integration" (Contract number N68171-94-C-9066), addressed the preliminary experiments being planned to demonstrate the range of novel capabilities achieved for the new facility. Recommendations were also made on staffing for the facility and a set of operating procedures were prepared for general use, Schofield and Steedman (1995).

This Final Technical Report covers the subsequent contracts Phase 4 (Contract Number N68171-95-C-9047), 4A (Contract Number N68171-97-C-9013) and 4B (Contract Number N68171-97-M-5713) entitled "Commissioning", which have followed the process of commissioning of the WES centrifuge center from the completion of the centrifuge in France through to its assembly and preliminary testing at WES, the initial research operations within a restricted working envelope, the achievement of the full design envelope in September 1997 and the inauguration of the centrifuge facility on 20 November 1997.

1.2 SUMMARY OF DEMONSTRATION EXPERIMENTS

Initial research work carried out during 1996 and 1997 using the new centrifuge covered a wide range of fields, and showed clearly the strong potential of this unique facility. Throughout the period of November 1995 to October 1996 an ANS&A research engineer, Dr K Stone, was resident in Vicksburg and this greatly facilitated training activities and the early completion of research experiments. Research experiments during the period 1996-1997 covered:

a) flow of immiscible fluids into sand beds;
b) buried explosions in dry and moist cohesionless soils;
c) large strain consolidation of soft mud, and upward migration of contaminant;
d) failure of silt slopes;
e) formation of 'multi-year' ice sheets;
f) earthquake response of a saturated soil bed.

Research projects for which experiments are currently being developed include:

g) the behaviour of airfield pavements under repeated loading,
h) beach formation processes under wave loading action.

The initial research projects were selected to maximise the involvement of other Laboratories and researchers. These included the Geotechnical, Hydraulics, Environmental, Structures, Information, Coastal and Cold Regions Laboratories. Training programmes were also presented, and a large number of Corps staff, potential sponsors and academics visited the facility in this period.

ANS&A has also assisted in promoting the use of the WES centrifuge in research applications. A range of proposals and other projects are under discussion with sponsors and potential collaborators in academic and commercial institutions. Several projects are awaiting funding. Early indications are encouraging and suggest that over the coming years, the centrifuge will be able to provide good levels of financial support for itself from a wide range of projects.

2.0 ASSEMBLY AND COMMISSIONING OF THE WES CENTRIFUGE

2.1 INSTALLATION OF THE 684-1 CENTRIFUGE

Phase 4 marked the most critical phase in the development of the WES Centrifuge Research Center as the new systems, including the centrifuge itself, came on line and were subject to load testing for the first time. In the case of the WES centrifuge, the 'stretching' of the Acutronic 680 design to accommodate a flat platform supporting two tonnes at 350g introduced a significant change to the original design concept, and this had consequential changes to the design of the platform and hanging straps. Factory Acceptance tests were limited to dimension checks because of the large size of the components, and load testing such as had been carried out on the original Acutronic 680 designed for LCPC in France could not be undertaken.

ANS&A's role with regard to the activities in France was to maximise the value to the WES of any changes during design and manufacture and to ensure that safety or useability of the facility was not compromised. In particular it was considered critical to ensure that the design factor of safety of 2.7 to the elastic limit was retained throughout the process.

During the early stages of Phase 4, Factory Acceptance Tests were undertaken in France and the centrifuge, which could not be fully assembled in the factory, was shipped to WES.

ANS&A proposed that commissioning of the centrifuge (termed 'mechanical commissioning' to distinguish from the commissioning of research capabilities) should be undertaken in two stages, with an interval of at least six months in between. In the first stage it was proposed that the centrifuge would be commissioned to around 200 - 250 gravities, and in the second stage the full design envelope would be achieved. During the period between the first and second stage commissioning, research activities could be undertaken and experience gained with the new machine. This would provide early access to research data, which would build confidence amongst the Corps research staff and sponsors, and would reduce the risk of accidents during the second stage.

In particular, ANS&A stressed the importance of WES retaining control of the operation of the centrifuge during commissioning, and of WES staff participating in the commissioning operation. A research engineer from the UK representing ANS&A, Dr K Stone, was posted to WES to assist with the commissioning and training process. This recommendation was considered necessary because the design of the WES centrifuge incorporated a number of novel features over earlier models in the Acutronic series, and because of its large size, which meant that the first operation of the fully-assembled centrifuge was the only practical means of demonstrating that the centrifuge met its specification.

The assembly of the centrifuge and first operation took place during the early months of 1996. The WES, supported by Dr Stone, participated closely in the first operations of the centrifuge. The first indication that certain parts on the centrifuge would not meet their specification arose when permanent strain was detected in the platform hangars at modest g levels.

The close vigilance of the WES and ANS&A engineers prevented further damage from

occurring. Subsequent inspections and testing confirmed that a number of parts, including critically stressed components, did not meet specification. However, it was concluded that the centrifuge could still be used for research purposes whilst the replacement components were manufactured, but within a reduced operating envelope.

2.2 COMPLETION OF COMMISSIONING

During the summer of 1996 negotiations continued between WES and the French suppliers and agreement was reached on the supply of the replacement parts. ANS&A participated in some of these discussions as technical advisors to WES. During the fall and winter of 1996/97 the replacement parts were manufactured in France by TLM. The parts to be replaced comprised the platform, the two platform hangars and six connecting pins, the outer boom divider (spacer), the rear boom spacer and the four feet. ANS&A regularly visited TLM on behalf of the WES, to confirm progress and to review QC paperwork.

The replacement parts (excluding the feet) were fitted to the centrifuge in August 1997 and in September the full design operating envelope of the centrifuge was proven. The feet were scheduled to be fitted in January 1998. For the 350g test run, circular lead weights (contained within steel bands) were used to provide the design value of 2 tonnes distributed load on the platform. The full speed equivalent to 350g at 6.0m radius was achieved without the use of the shrouds, although this may have been partly due to the low profile of the lead weights on the platform. Temperature rise in the chamber was substantial, reaching in excess of 45 degrees C.

With this final stage of commissioning complete, the restrictions on the centrifuge operating envelope were lifted. Throughout this period ANS&A provided close technical support to WES, including the development of operating procedures based on principles developed at Cambridge University, where there is a division of responsibility between the operator of the centrifuge, the research worker and the engineer. These procedures were formally introduced at the start of the research operations, which followed the first stage of mechanical commissioning.

3.0 DEVELOPMENT OF NOVEL RESEARCH CAPABILTIES

3.1 PLANNING

During the final stages of Factory Acceptance and shipping, ANS&A prepared an initial experiment plan for the centrifuge facility which included basic testing (proof testing) of equipment, and experience of data aquisition systems, including the central arm services which were to be fitted to the centrifuge following installation.

In parallel with the fabrication of the centrifuge in France ANS&A had completed considerable technical development of key systems and appurtenances in Cambridge, including concepts for temperature control of model chambers in flight using vortex tubes driven by compressed air and for the formation of ice sheets in flight using a 'black sky' and cold gas generator. Development of the earthquake actuator was also proceeding, with testing of a prototype unit on the Cambridge beam centrifuge in parallel with design development of the large actuator to be provided for the WES.

Appurtenances and user equipment were shipped in stages to WES and assembled under the supervision of ANS&A's resident engineer. One of the first major units to be assembled and integrated with the centrifuge was the central arm services, which was to be used to monitor the instrumentation on the centrifuge during the initial proving flights.

The restriction to the operating envelope caused by the discovery of sub-specification components had minimal consequences for the research programme, as the programme had been prepared with a two stage commissioning process in mind. The first research experiments were conducted in 1996, addressing groundwater problems, failure of silt slopes and cold regions and these are discussed below.

ANS&A recommended that the restricted operating envelope which should be used during this phase should be based on a Factor of Safety of 1/2.7 to the maximum load point reached, and with further monitoring, this could be relaxed to 1/2. This approach would be closely in line with the design philosophy of the centrifuge itself.

3.2 DEVELOPMENT OF NOVEL CAPABILITIES

In support of the transfer of technology to the WES (the principal objective of ANS&A's response to the 1989 BAA) substantial resources were devoted during the period of research covered by this report to the development of the novel research capabilities of the new centrifuge and to the commissioning of the wide range of equipment and appurtenances which had been developed in Cambridge in parallel with the fabrication of the centrifuge in France. Although the majority of this equipment was designed and fabricated in the UK certain components were procured from other sources, where it was regarded that benefit could be gained from calling upon their specialist experience. Thus the piezotip for the cone penetrometer was procured from ISMES in Italy, and the 2D actuator was designed and built by engineers associated with the centrifuge centre at the University of Western Australia, Perth.

The equipment from Cambridge was air-freighted to the WES from the UK in a series of shipments, as noted above, and was then proof tested on the WES centrifuge. Dr Stone was assisted in this task over a period of some months by a research mechanical

engineer, Mr K Dimitriadis, also from the UK. ANS&A's mechanical design engineer, Mr Keith Wilkinson, made short visits to the WES during the period to assist in this process. Dr Steedman visited the WES frequently to monitor progress and to provide support and advice. Professor Schofield also visited on a regular basis.

The commissioning of capabilities was completed by carrying out demonstration experiments, deliberately selected to utilise all appurtenances and to involve many of the different Laboratories which may in future be further involved in the new center. These demonstration experiments therefore served several purposes, and provided an opportunity for training and for gathering experimental data which could be used in support of future research proposals. Some of the experiments completed during this period are outlined below.

Groundwater models were conducted as a joint research experiment between the Hydraulics and Geotechnical Laboratories. The experiment was designed to investigate the dispersion of an immiscible fluid (a silicon oil) into a water saturated sand bed. Within the 1.2m diameter standard tub, the model included four separate sites, each with 'droppers' which could release the contaminant into the sand below at different times. Samples excavated after the experiment were subjected to MMR and radiographic analysis to determine the size of the plume, for comparison with numerical models.

Work at the Geotechnical Laboratory into the failure of silt slopes in the field under changing groundwater conditions was used as the basis for a demonstration experiment which would provide experience in sample preparation, use of the large downward hydraulic consolidometer and the plane strain box. Models were constructed from a silt loess, a local soil, by consolidating a block of soil from slurry using the large consolidometer developed especially for the centrifuge facility. A slope was then cut into the block which was brought to failure under increasing gravity. The failures closely resembled field events. Following this, other models were constructed using block samples from the field.

Thirdly, in connection with possible future collaboration with the Cold Regions Laboratory, the 'black sky' cold gas generator technique which had been pioneered in Cambridge on a small chamber was further developed on a large scale to freeze an ice sheet within the 1.2m large square box. Part filled with insulating material, the frame supporting the black sky unit was mounted above the box, and using frozen carbon dioxide, an ice sheet was formed in flight on the surface of the brine below.

The provision of an earthquake shaker, both in support of studies into liquefaction being undertaken by the Geotechnical Laboratory and in the field of soil-structure interaction (such as the behaviour of lock walls) involving the Information Technology Laboratory was deemed essential at an early stage in the development of the new center. Designs for a robust cost-effective shaker which could provide strong shaking to the base of a deep specimen at upto 150 gravities were developed over a period of years, while a close watch was maintained on possible alternative actuator solutions. The ESB concept for model containment (Equivalent Shear Beam) was selected based on experience at Cambridge and a mechanical actuator using stored angular momentum was eventually chosen as the most robust design likely to provide shaking at high gravities within a realistic budget and timeframe. A small system was built for Cambridge University as a proof of concept, and this unit was then flown on the WES centrifuge in

1996 to provide the first data of dynamic model experiments and the first academic collaboration with the new center. These first earthquake experiments were conducted on dry and saturated sand samples. This series of work was concluded in January 1997.

Later the same year the assembly and commissioning of the new WES earthquake actuator was finally completed. The design of the large actuator followed the principles of the smaller Cambridge unit (using stored angular momentum as the energy source) but incorporated a number of new features. The depth of the ESB (Equivalent shear beam) container was increased to 600 mm (60m at 100 gravities) and the centroid of the reaction mass was positioned above the shaking platform, at an elevation approximately opposite the centre of mass of the specimen, thus minimising any tendency towards rocking.

Experiments using the new shaker and ESB container have investigated the propagation of strong ground motion through dry and saturated sand beds. These experiments have provided the first data towards a major research effort in the study of the liquefaction of sand layers under different effective overburden stresses.

Similarly, experience of blast models carried out some years before on the Cambridge centrifuge was used to support the design of the blast chambers for WES. These chambers were designed to withstand a high static internal gas pressure but in the event of overpressure the stack assembly would 'vent before break', to minimise the risk of catastrophic accident. The chamber could be assembled from either steel or aluminium rings, with an internal diameter of 850mm, depending on the user's requirements for a low or high g experiment. (It was anticipated that most experiments would utilise the more robust steel rings, but because of weight constraints experiments at high gravities could use the lighter aluminium kit with a similar margin of safety.) The blast chamber was successfully proven using high explosives at 1g, detonated underwater. Strains were measured on the chamber and found to be small, and the chamber was subsequently used on the centrifuge for a series of blast experiments in dry and moist sand carried out under the direction of the Structures Laboratory. These experiments were similar to, although not exactly scaled models, of the field experiment MIDNIGHT HOUR 2, a cratering experiment using buried HE charges. The resulting crater profiles bore a close resemblance to the field event.

Research in collaboration with the Environmental Laboratory focused on the consolidation of dumped dredge disposal and the movement of contaminants into the cap. A series of experiments were conducted to investigate firstly, the properties of the sludge, and secondly to model the various stages of dumping, cap placement and long term performance. A purpose built specimen container was constructed which could be fitted within the small 420mm diameter circular chamber intended primarily for environmental applications or long term centrifuge runs which required temperature control. Tracers included radio-isotopes and coloured dyes, and the success of the early experiments has led to further work opportunities.

Two other key demonstration experiments are presently under design. In collaboration with the Mobility division, specialist tools such as the 2D load actuator, have recently been commissioned and will be used in studies including the behaviour of deep airfield pavements under wheel loading.

Secondly, the design and fabrication of a rectangular chamber which could overhang the centrifuge platform was intended to provide an opportunity for 'long' models, particularly models involving wave action and beach processes, to be developed. Plans have been completed in collaboration with the Coastal Engineering Laboratory (recently merged with the Hydraulics Laboratory) for a demonstration experiment using the long box to investigate processes of beach formation, and this is expected to be completed in 1998.

The demonstration experiments provided an important route by which researchers in Laboratories outside the Geotechnical Lab could gain first hand experience of the new facility and could establish contacts with the center management. In addition to these activities, ANS&A also organised training sessions for a wider audience of prospective centrifuge users at WES to raise awareness of the center and to provide guidance in experiment design, model preparation techniques, centrifuge theory and practice.

The period of research also covered a wide range of activities associated with the marketing and promotion of the center externally. A brochure was developed to promote the centrifuge and a series of papers describing the center and the initial research experiments were prepared for conferences and for attachment to the WES home page. The inauguration of the centrifuge took place at short notice on 20 November 1997. Although ANS&A representatives were not present, materials were prepared and detailed advice was provided to assist in the layout and presentaion of the demonstration experiments to be used in the briefings.

4.0 CONCLUSIONS

The BAA of December 1988 called for new capabilities in physical modeling research. ANS&A's response of 17 April 1989, to develop a new large centrifuge facility at the WES, with trained staff and a wide range of specialist and general purpose appurtenances, and to prove this concept by the achievement of research experiments across the range of desired capabilities, has been realised.

Three factors have contributed most significantly to this accomplishment.

Firstly, the recognition that from the outset it was necessary to consider in detail the likely research projects that would be undertaken using the new facility. Thus, as design of the centrifuge and the containment building proceeded (under separate contracts to ANS&A), the implications of change could be readily assessed and appropriate decisions made quickly.

The focus on the research product of the center ensured that as the need for appurtenances was discussed and ideas were developed, each kit had an early requirement for use, and provided a different opportunity for training and the development of model construction techniques. As soon as the centrifuge became available, a wide range of experiments were also ready for testing.

Secondly, the emphasis on safety of components and safety of operations at all stages, from design specification to commissioning and operation, meant that when problems arose, procedures were in place to manage the situation and to minimise the risk of a major accident.

Thirdly, the continuity of key staff over the lifetime of the project, at WES, within ANS&A and with the designers of the centrifuge in France, was a vital ingredient in the final accomplishment. Knowledge of the background and history, the contractural and technical obstacles, and the overall objective of the BAA were essential to the satisfactory completion of the project.

Finally, the inauguration of the Centrifuge Research Center on 20 November 1997 marks an academic achievement also. The large centrifuge at the WES is a unique facility both in its potential for delivering research product and in its potential for supporting academic and practical engineering applications.

REFERENCES

Schofield, A.N. and Steedman, R.S. (1991) Safety Factor Analysis for Centrifuge Systems, Final Technical Report, ANS&A Report 26-01-R-001 for US Army European Research Office, London (Contract No. DAJA45-90-C-018).

Schofield, A.N. and Steedman, R.S. (1992) Development of a WES Centrifuge, Final Technical Report, ANS&A Report 26-02-R-004 for US Army European Research Office, London (Contract No. DAJA45-91-C-0012).

Schofield, A.N. and Steedman, R.S. (1993) Design of the WES Centrifuge (Phases 3A & 3B), Final Technical Report, ANS&A Report 26-03-R-006 for US Army European Research Office, London (Contract No. DAJA45-92-C-0021).

Schofield, A.N. and Steedman, R.S. (1995) Coordination of operations for centrifuge quality control (Phase 3C), Final Technical Report, ANS&A Report 26-03-R-009 for US Army European Research Office, London (Contract No. DAJA45-93-C-0021).

Schofield, A.N. and Steedman, R.S. (1995) Integration (Phase 3D), Final Technical Report, ANS&A Report 26-03-R-012 for US Army European Research Office, London (Contract No. N68171-94-C-9066).